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Shear Strength Reduction Analysis of Slope by Numerical Modelling Based on Finite Element Method

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Abstract: The stability of the slope is the crucial factor in geotechnical engineering, particularly when the slopes are composed of soils. The purpose of this research is to analyze the shear strength reduction of glacial till slope using phase 2 software. Where, conclusive analysis is based on two methods, Limit equilibrium and the Mohr-Colomb criterion Finite Element (FE) Shear Strength Reduction (SSR). The methodology embodied the major laboratory test results such as Atterberg limits, Direct Shear Strength test, unconfined compression strength. The experimental results were than used in phase 2 software, where 2D plane strain model of the slope was created. The impact of modifications in shear strength parameters on the factor of safety is then examined. The analysis showed that the glacial till slope experienced a significant reduction in strength, with the Limit Equilibrium method FOS ranging from 0.94 to 1.54, while Mohr's criterion Finite Elements Shear Strength Reduction ranged from 0.31 to 0.61. The analysis results, in conclusion, the shear strength reduction of slope is reliable and efficient for determining the stability of slopes. The use of both aforementioned methods provides accurate and consistent results that can aid in making effective engineering decisions.

Keywords: Limit Equilibrium Method, Strength Reduction Method, Stability Analysis, Factor of Safety, Slope

1. Introduction

Examining and assessing any slope is one of the most important components of engineering geology for any sort of construction. Numerous indo and exo-genetic earth processes affect the slope, which have an impact on its stability over time. Numerous factors, such as the quantity of rainfall, the materials used to construct the slopes, their condition, etc., affect their stability. Depending on the materials found on the slope, they each have a different value for the strength parameter. Because the material's shear strength is often insufficient to withstand the actual shear force, the slope frequently collapses. Therefore, the Factor of Safety (FOS) value is used to determine the stability criteria for the slope. The Finite Element Method is the most widely used for slope stability analysis throughout the world. Depending on the nature of material different analysis is based on different criterion. The Hoek-Brown emphasize more on the strength of rock mass characterized by elastic-brittle-plastic behavior of materials that has well defined plastic flow [8] whereas the Mohr–Coulomb criterion is simple linear elastic perfectly plastic model characterized for the strength of soil [11]. The most important aspects while analyzing any slope is its slope stability and determination of its factor of safety [1]. The factor of safety of the slope is the ratio of shear strength of the soil to the minimum shear strength needed to stop the failure [2-4]. The factor of safety (FOS) of the soil slope presented here is the number by which the shear strength value must be divided to bring the slope to the stage of failure [5].

The slope is stable if the condition of FOS value is more than one; unstable if it is less than one [2]. This is achieved here by repeating the sequence of strength reduction values [5]. In the procedure known as "slope stability by strength reduction," the soil is weakened in a variety of plastic finite element, studied until the circumstances of the slope is breakdown. The finite element method (FEM) is the technique that is most frequently used for slope stability analysis [3]. The key advantage of using FEM over other techniques is that it does not need to make any assumptions about where the failure surface will be and how far the slope will advance [9]. The generic model is then made up of Coulomb and numerous other investigations.

The strength reduction method for the Finite Elements Method (FEM) for the calculation of factor of safety (FOS) of soil slope is that the soil slope fails until it gradually meets the decreased strength parameters of soil [2-4]. When utilizing the finite element method to analyze slopes, there are often two approaches. Either the gravitational load conditions can be elevated or the strength characteristics of slope materials can be decreased. Shear Strength Reduction (SRR) is a technique or idea that computes the slope's FEM model while gradually reducing a material's shear strength by a safety factor until deformation is intolerably high [7]. The study has three key variables that affect the stability analysis which are the slope's material properties, how the safety factor is calculated to affect slope stability, and how slope failure is defined. The materials for the stress reduction analysis are gathered from the properties of glacial till, which is a collection of unsorted materials that glacier deposited without using any sorting techniques. Examining the failure conditions is done in a variety of Stress Reduction Factor (SRF) scenarios with different soil parameter values. Phase 2 is one of the methods that are most usually applied to make sure that the surface and underground structures are appropriately planned, assessed, and supported in the domains of engineering geology, geotechnical engineering, and mining engineering [10].

2. Shear Strength Reduction Method

The shear strength reduction approach, a slope stability study methodology that combines the systematic use of finite element analysis, can be used to identify the Stress Reduction Factor (SRF) [7] Or factor of safety value that brings a slope to the verge of failure. The FOS used in strength reduction method is:

$$C_{failure} = \frac{C_{ini}}{SRF}$$

$$\varphi_{failure} = \tan^{-1}\frac{\tan(\varphi ini)}{SRF}$$

$$\text{FOS} = \text{SRF}_{\text{at failure}}$$

Where φ_{ini} and C_{ini} are the initial values of the friction angle and cohesion, respectively, and $\varphi_{failure}$ and $C_{failure}$ are the friction angle and cohesion, respectively, that cause imminent failure. To obtain minimum value of the FOS, the FEM needs to change the SRF factor gradually [6].

The slope's finite element model is reduced via SRF. Therefore, the conventional analysis of slope using a finite element model is performed up until a critical SRF value induces instability is reached. The slope is regarded as unstable in the SSR technique if the finite element model fails to converge to a solution inside a specified tolerance.

3. Methodology

The primary assignment for this study was a desk study that entailed carefully reading a variety of works of literature that were relevant to the topic. After the desk study, lab tests, and sample analyses were conducted. The process of conducting research is depicted in the diagram below (Figure 1).

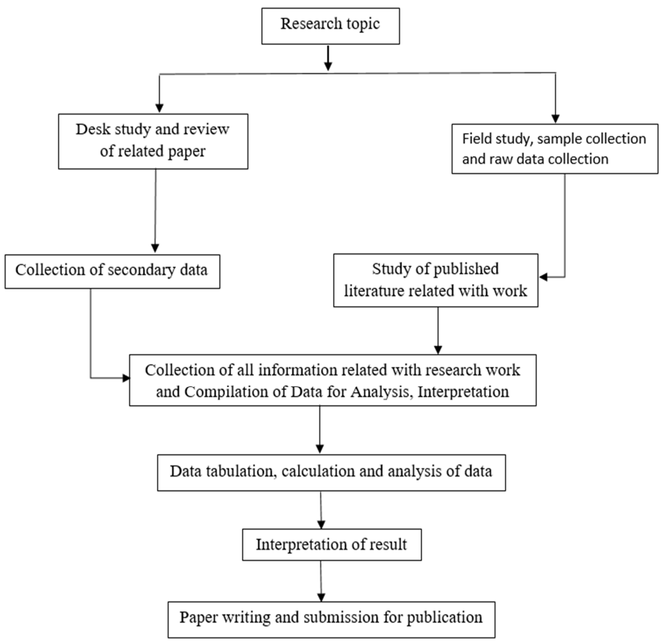


Figure 1. *Methodology flow chart of the research.*

4. Result of Study

Results of material testing in laboratories

The many characteristics of till materials, including their mechanical, hydrological, physical, etc., were examined in the lab in order to assess the slope's stability using the Shear Strength Reduction method. One of the most crucial elements that were examined in the lab included the stability of the till-containing slope. Other examinations included testing for moisture content, compaction, and sieve analysis. The test findings are summarized in the table (Table 1) below.

Table 1. *Laboratory test result.*

Sample No.	Dry Density (g/cm^3)	Optimum Moisture Content (%)	Unit Weight (KN/m3)
1	1.8	18.2	19
2	1.91	17.1	18.99
3	1.98	17.6	19.2
4	1.92	17.8	19

Numerical analysis

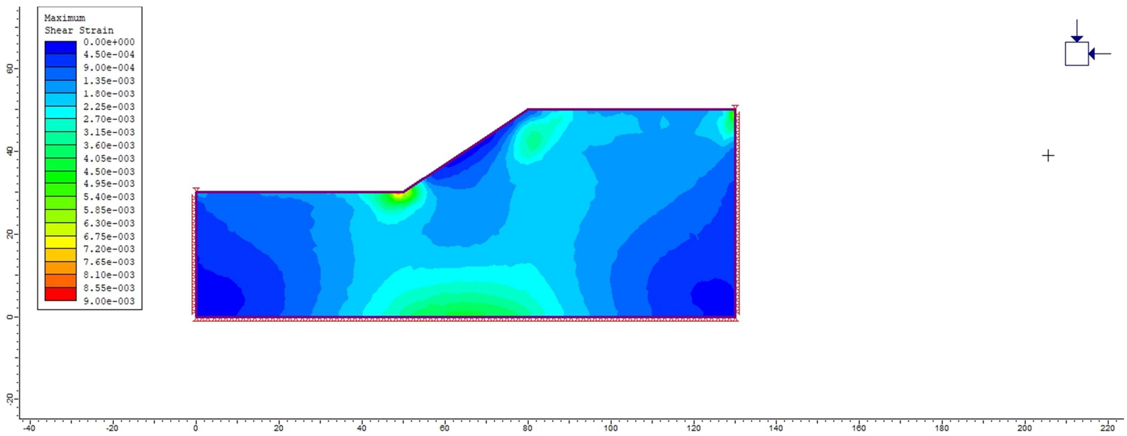
The strength reduction approach, also known as the factor of safety of the finite element method, is used in the study due to its ability to pinpoint the critical failure surface. The application of the strength reduction approach to complicated geometries, boundaries, and loading scenarios is its main advantage. Information on the strain, pore pressure, and other parameters can also be easily acquired. Different SRF value settings, which are discussed and illustrated in more detail below, were used to conduct the study for phase two. The SRF (strength reduction factor) numbers are displayed in the tabs at the bottom of the screen. By default, the important SRF tab is chosen. By default, the maximum shear strain dataset is selected and contoured. Maximum shear strain will be a helpful sign of where the slide is occurring, particularly if we change the perspective to higher SRF values. The numerical modeling input parameter is shown in the table (Table 2) below.

Table 2. *Input martial properties.*

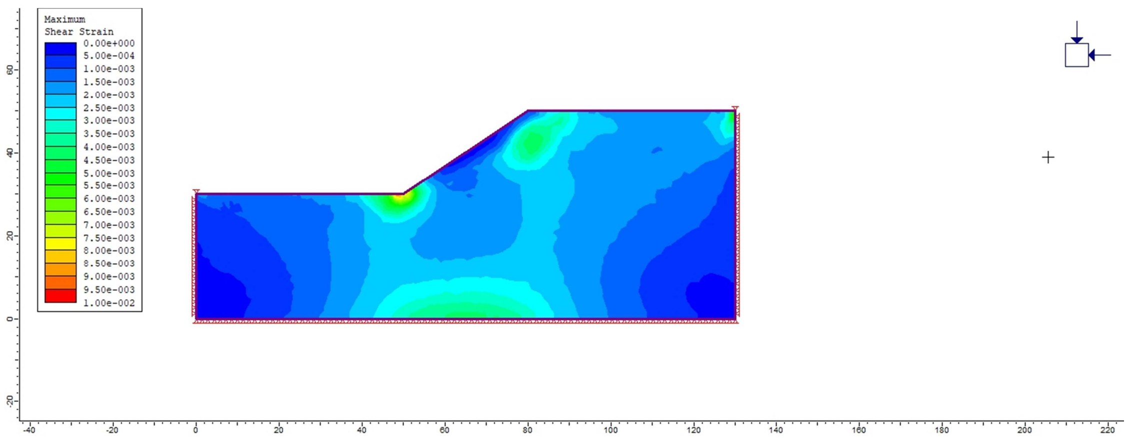
E_i	$\phi_{residual}$	$\sigma_{residual}$ (Kpa)	σ_{peak} (Kpa)	C_{peak} (Kpa)	$C_{residual}$ (Kpa)	ϑ
5000	30	5	5	5	5	0.4

Where, E_i = Youngs modulus
$\sigma_{residual}$ = Tensile strength
σ_{peak} = Tensile strength
$\phi_{residual}$ = Friction angle
ϕ_{peak} = Friction angle
C_{peak} = Cohesion
$C_{residual}$ = Cohesion
ϑ = Poisson ratio

Analysis in terms of maximum shear strain.

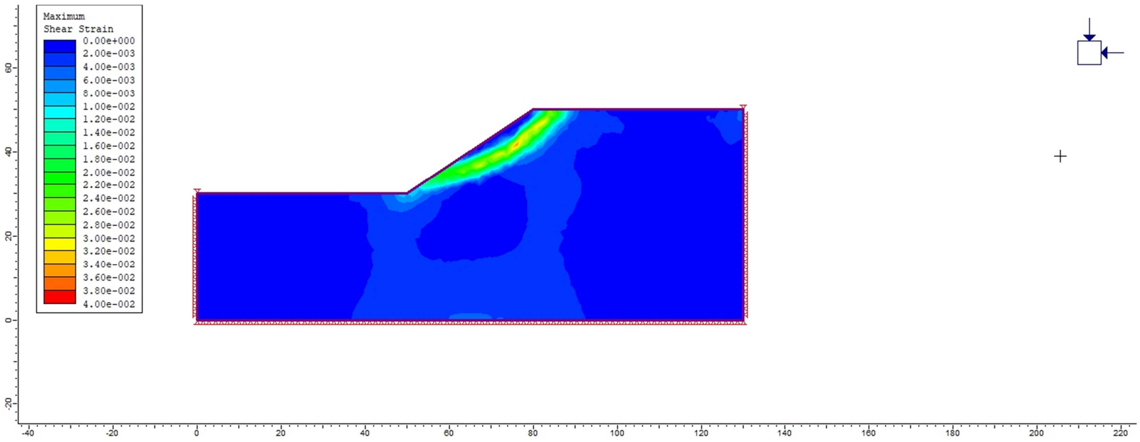


(a) Strength Reduction Factor =1.

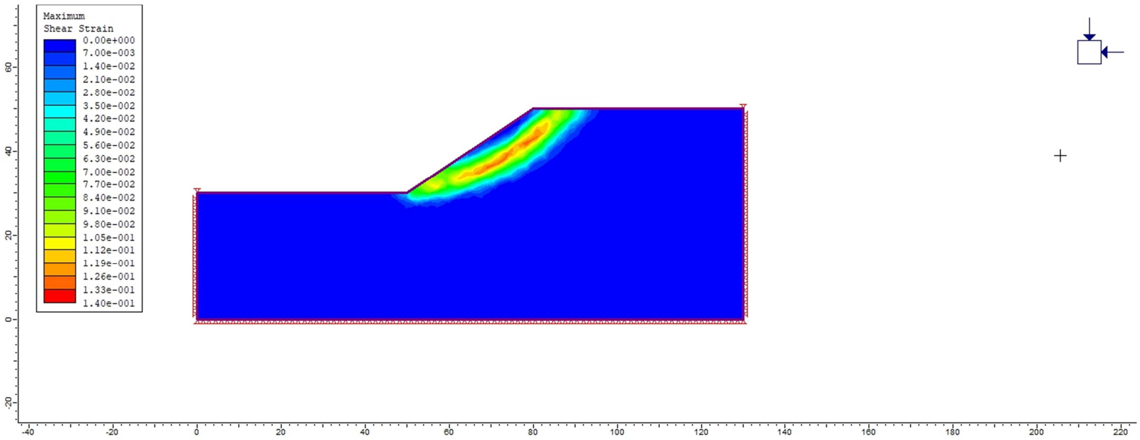


(b) Strength Reduction Factor = 1.15

The analysis begins from the stage at that conditions no failure plane is shown i.e. at conditions from SRF= 1 to SRF = 1.15.

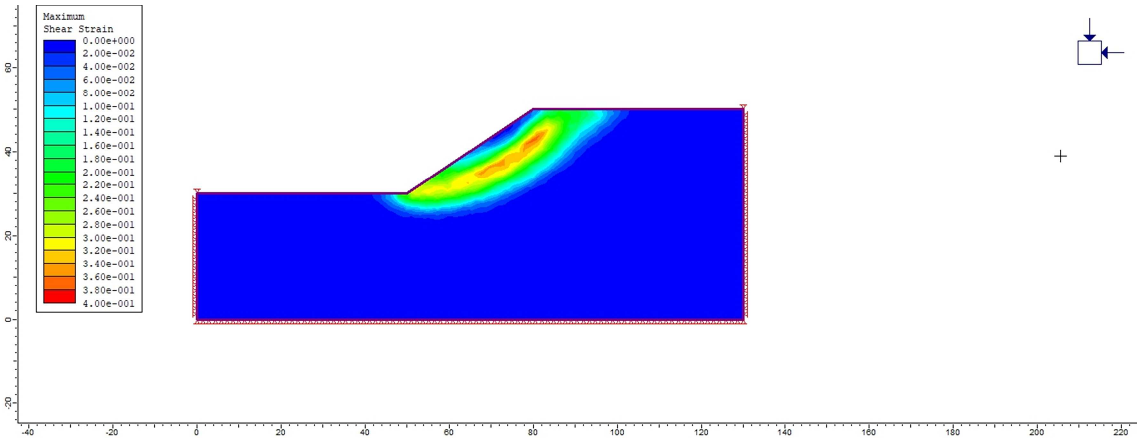


(c) Strength Reduction Factor = 1.16



(d) Strength Reduction Factor = 1.37

The failure plane is clearly seen at the condition of the Strength Reduction Factor reaches 1.37.



(e) Strength Reduction Factor = 1.75

Figure 2. *(a)-(e) Maximum shear strain analysis of Slope on Phase2 at different conditions of Strength Reduction Factor.*

Table 3. *The values obtained during numerical analysis.*

Stage	Strength Reduction Factor (SRF)	Maximum Shear Strain Value
1.	1	0
2.	1.15	0.01
3.	1.16	0.04
4.	1.18	0.06
5.	1.37	0.14
6.	1.75	0.40

The graphical plot (Figure 3) of the strength reduction factor and maximum shear strain value is given below.

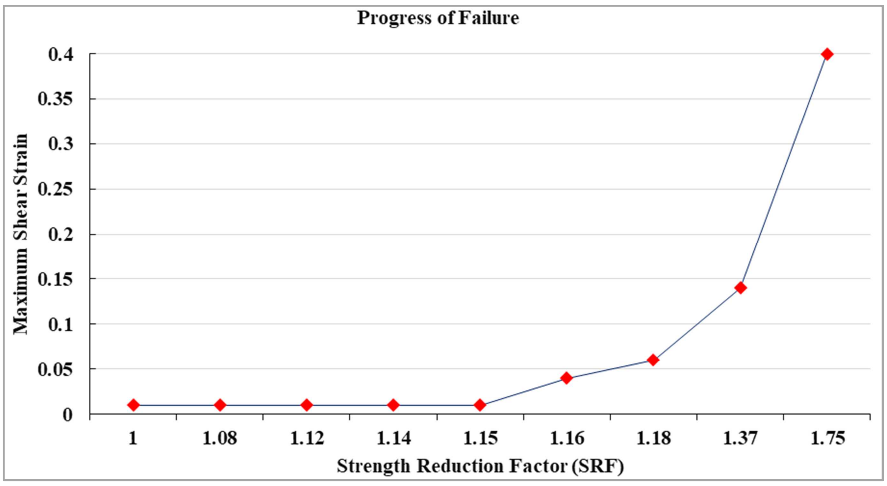
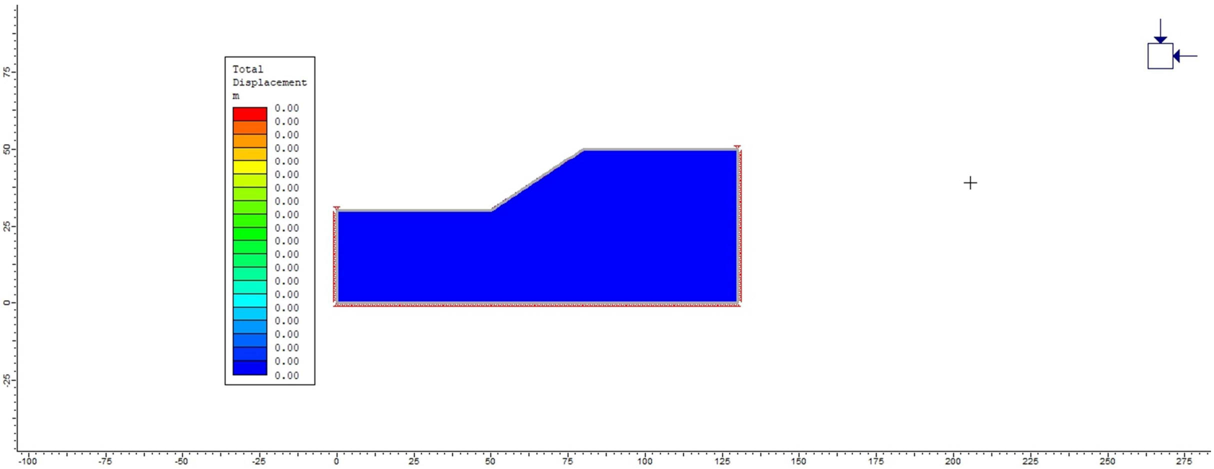


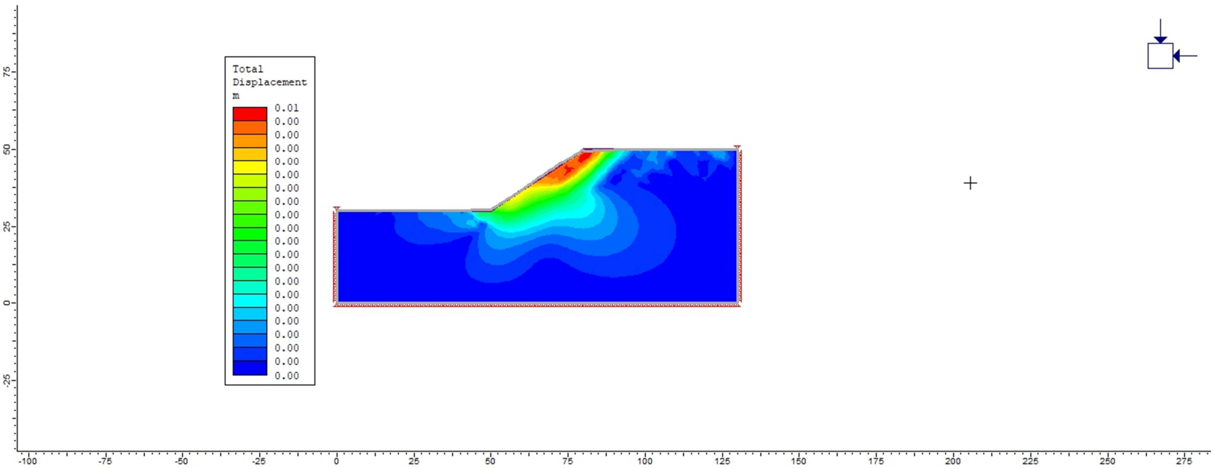
Figure 3. *Shows the progress of failure with SRF.*

Finally, when the Strength Reduction Factor value reaches 1.75, the failure surface may be plainly seen. Increases in strength cause reduction factors and failure surfaces to rise. As a result, the slope's shear strength decreases under those circumstances. When the SRF value reaches 1.75, the shear band is clearly visible.

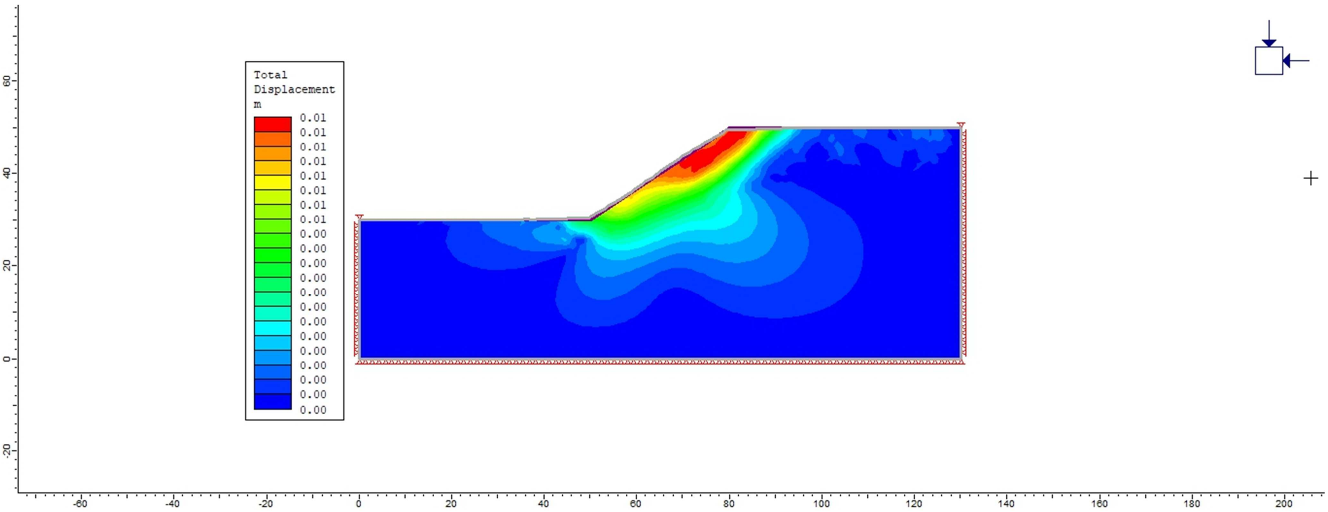
Analysis of slope in terms of total displacement



(a) Strength Reduction Factor = 1
At SRF value 1 no sign of instability on the slope.

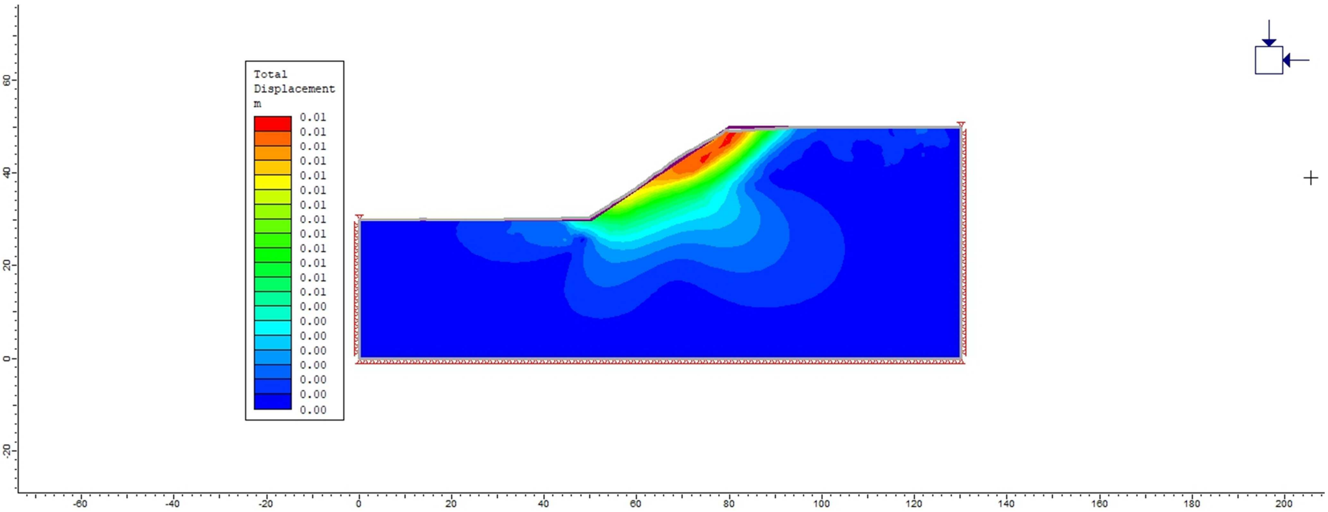


(b) Strength Reduction Factor = 1.08

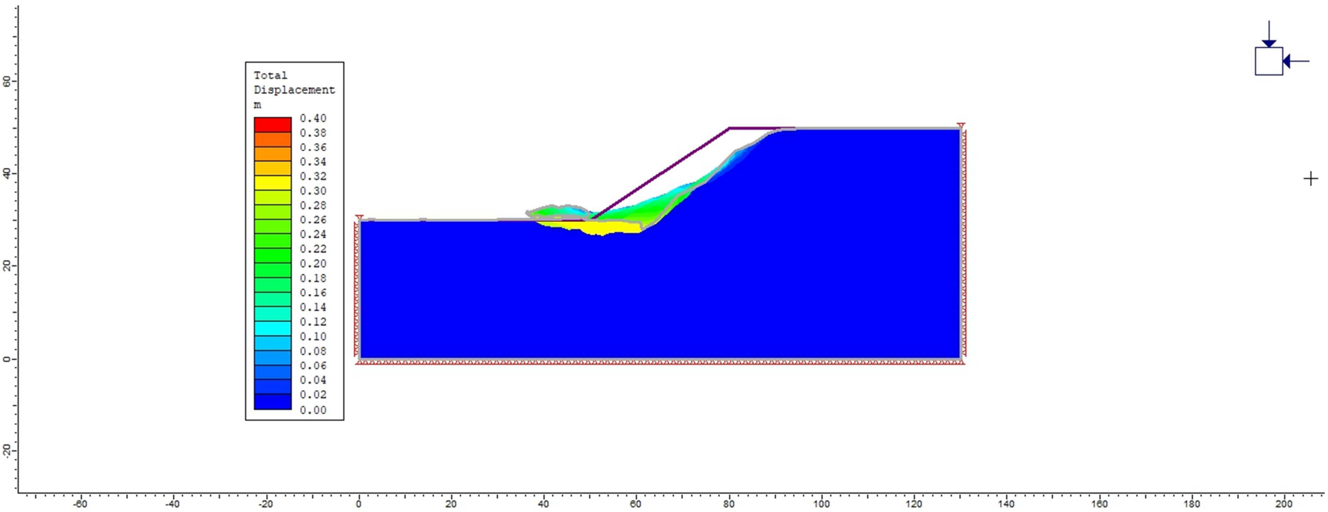


(c) Strength Reduction Factor = 1.12

At SRF 1.08 to 1.12 in which the different deform contours and deform boundaries can be seen. In which the value of total displacement gets increased from 0 m to 0.01 m. This indicates the progress of failure with the increase in the SRF value.

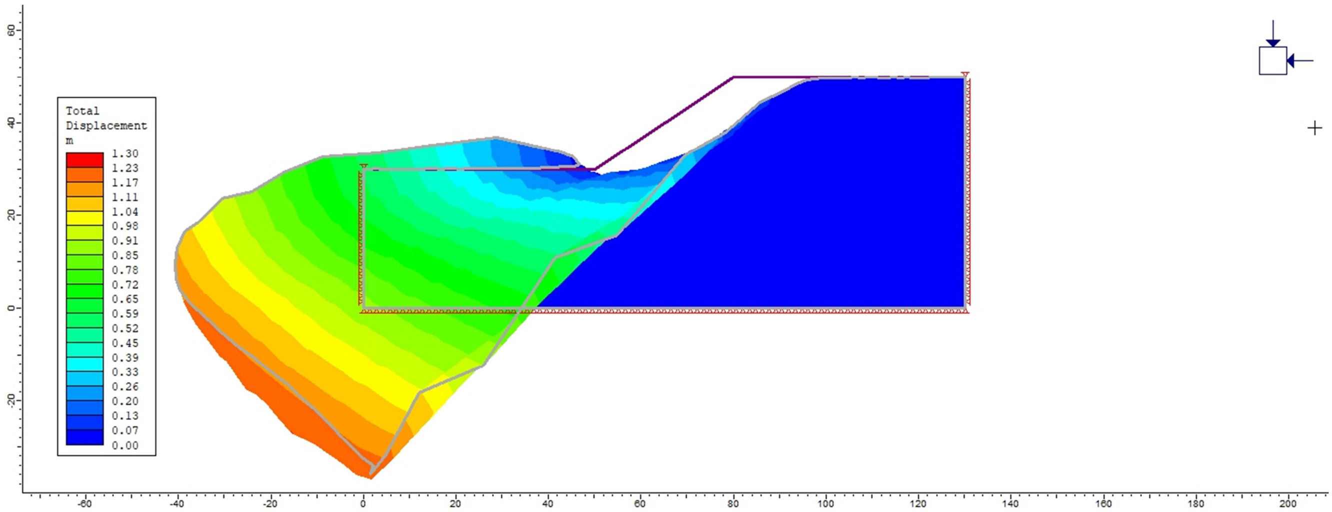


(d) Strength Reduction Factor = 1.15

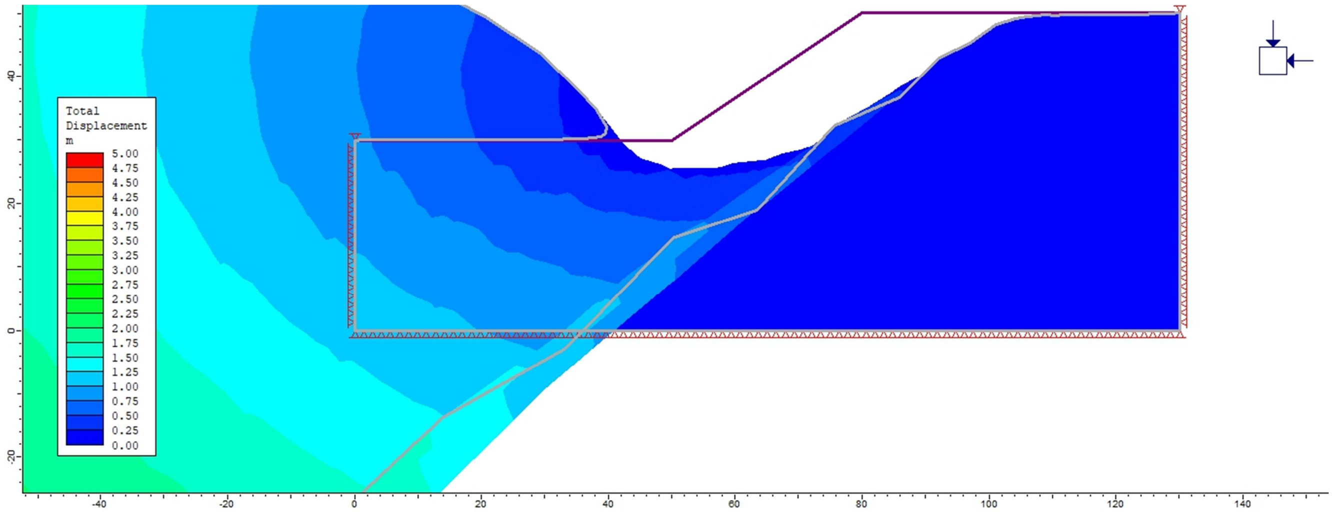


(e) Strength Reduction Factor = 1.18

In which the displacement of the slope materials can be visible at SRF value increased at 1.18. Then the displacement value gets an increase from 0.01 m to 0.30 m.



(f) Strength Reduction Factor = 1.37



(g) Strength Reduction Factor = 1.75

Figure 4. *(a)-(g) Total Displacement analysis of slope at different conditions of SRF value.*

The slope materials start to be entirely displaced when the SRF reaches 1.37, and the same thing happens when it reaches SRF 1.75. The overall displacement (Table 4) is then depicted graphically below (Figure 5).

The graphical plot between the strength reduction factor and total displacement is given below.

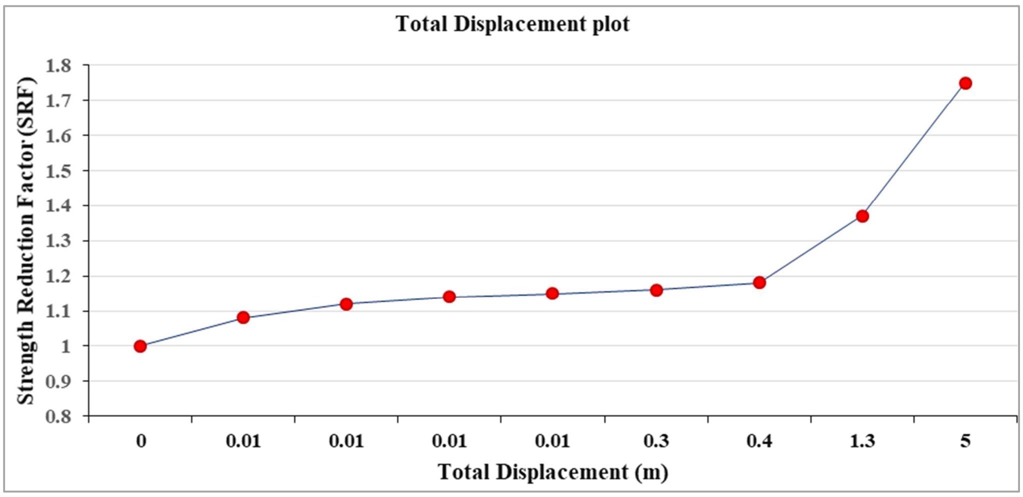


Figure 5. *Graphical plot of total displacement.*

Table 4. *Numerical analysis data of total displacement analysis.*

Strength Reduction Factor (SRF)	Total Displacement (m)
1	0
1.08	0.01
1.12	0.01
1.14	0.01
1.15	0.01
1.16	0.3
1.18	0.4
1.37	1.3
1.75	5

5. Conclusion

This study concludes that with an increase in SRF value, the strength properties of materials get decrease when strength decreases the maximum displacement gets increases. At some conditions, the slope will fail then the deformation trend rises. In such a condition the FEM methods can not cover all the results. In its research work the hydrological, mechanical, and physical properties of the till materials were used for the analysis of slope then the different numerical input parameters were generated from the various laboratory analysis. To analyze the slope stability, the dry density test, optimum moisture content test, and unit weight test were conducted in the laboratory with major care, similarly, the different parameters such as Young's modulus, friction angle, tensile strength residual, tensile strength peak, cohesion residual, cohesion peak were and Poisson's ratio. Using this all the parameters from the analysis in terms of maximum shear strain when the SRF value reaches up to 1.75 failure possibility of the slope is clearly seen. Further, an increase in strength cause reduction factors and failure surfaces to rise. As a result, the shear strength of the slope decreases under those circumstances. When the slope SRF value gets 1.75 the shear and slope begins to form. In the analysis using the concept of total displacement when the slope materials start to be entirely displaced when the SRF reaches 1.37 and the same things happen when it reaches SRF 1.75.

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